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# Electric field measurement using a non-perturbative method based on a calibrated electric potential sensor

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**Abstract.** We present results of finite element analysis for simple test structures which demonstrate clearly that the measurement situation is complex. The test structure consists of an open geometry parallel plate capacitor within a screened enclosure. Indeed, the presence of earthed objects, even at considerable distances, is shown to have a significant effect on the field geometry close to the source. These simulations are compared with field measurements made using an ultra-high input impedance sensor, the Electric Potential Sensor. A single experimentally determined calibration factor is all that is required to achieve excellent agreement between experimental measurements and the results of the simulations. Given this, the sensor is capable of mapping accurately, and in a non-perturbative manner, the spatial potential both within and outside of the test structure.

## 1. Introduction

It is often assumed that the loading effect which an electrostatic field meter (ESFM) imposes on the electric field to be measured is well understood. In particular, that this may be accounted for using a simple capacitance calculation. In practice, the loading of the electric field by a meter is more complex than this, especially if the measuring electrode is intricate and/or within the unit. This can introduce measurement errors in excess of 100% [1], which can be a direct result of the meter or the method used to make the measurement. A non-invasive or non-perturbing way of measuring electric field is necessary in order to make reliable and accurate measurements.

There have been a limited number of specialized ESFMs developed over the years to measure electric field in a variety of environments but more so in industrial settings [2]. A recent development and addition is the Electric Potential Sensor (EPS or EP sensor). The EP sensor is a highly diverse ultra-high input impedance device with unique feedback circuitry, which achieves a high level of sensitivity. The EP sensor is a patented technology invented at the University of Sussex and has had a multiplicity of applications. These include imaging of active electrical circuits [3], electric field nuclear magnetic resonance signal detection [4], and imaging of charge spatial density on insulating materials [5]. Generic electrical specifications for an EP sensor are; input capacitance  $<10^{-15}$  F; input resistance  $>10^{13}$   $\Omega$ ; bandwidth quasi d.c. to  $>100$  MHz. It needs to be stated here that the EP sensor does not have a true DC response. However, static charge information can be recovered if the sensor is moved in a well-defined step motion [5]. The sensor specifications and response characteristics are described in our earlier publication [6]. This publication also outlines the high level of sensitivity of a calibrated sensor in a controlled electrical environment.

It is the intention of the authors to demonstrate that EP sensors may be used as non-perturbative field meters with extremely high sensitivity and the capability to work in unshielded environments. Progress has already been made using EP sensors in applications that bring them into open noisy environments [7]. A comparison of independent simulations and measurements are presented here. These findings present the possibility of making viable EP sensors as future ESFMs.

## 2. Experiment and simulation methodology

The experimental and simulation setup is similar to our treatment found in our prior publication [6]. An overview of this, together with a description of the measurement methods used is given here. The experiment is conducted within an aluminium Faraday enclosure, which sets the grounded boundary conditions. The physical enclosure has the dimensions 3.65 m (l) x 2.45 m (w) x 2.45 m (h). We adopt the Cartesian coordinate system to relate to the  $x$ -axis as the length,  $y$ -axis as the width, and  $z$ -axis as the height (see insert in figure 1). These dimensions and material parameters are modelled in the computational simulations of electric field distribution.

In the practical setup, a calculable electric field is generated within the enclosure using an aluminium parallel plate capacitor, measuring 1 m x 1 m with a non-metallic spacer producing 0.6 m of separation. The experiments carried out use an a.c. source to drive one of the plates with a voltage while grounding the other. For the practical experiment an a.c. voltage source with 10 V<sub>pp</sub> at 158 Hz is used. This frequency is chosen to avoid multiples of the mains harmonics and to be within the bandwidth of the EP sensor. For the simulated excitation, a static 10 V is applied to the source plate. This produces the same instantaneous fall-off in potential across the plates as an a.c. signal and reduces the computation time required. The grounding of one plate and driving of the other is referred to as an *unbalanced excitation* mode.

The electric field measurements between the plates are made using the EP sensor. The EP sensor is mechanically supported externally to the parallel plate cavity, allowing a semi-rigid coaxial electrode to protrude into the desired measurement location. The unique electrical design of this EP sensor incorporates a guard driven outer coax of the electrode. This guard signal follows the measured potential to a high level of precision, with the effect of eliminating any perturbation on the generated electric field. This is only achievable by placing the electrode in a plane of near constant potential, namely the  $zx$ -plane. The electric field to be measured is coupled to a square copper electrode tip soldered to the inner coax, which has an area of 1 cm x 1 cm. This tip couples to the electric potential for a given measurement axis in either the  $y$ -axis through the centre of the plates, or along an  $x$ -axis that is at the mid-height of, and parallel to, the plates. For  $y$ -axis measurements the position is relative to the source plate. For the  $x$ -axis measurement, the coordinates are relative to the  $yz$ -plane.

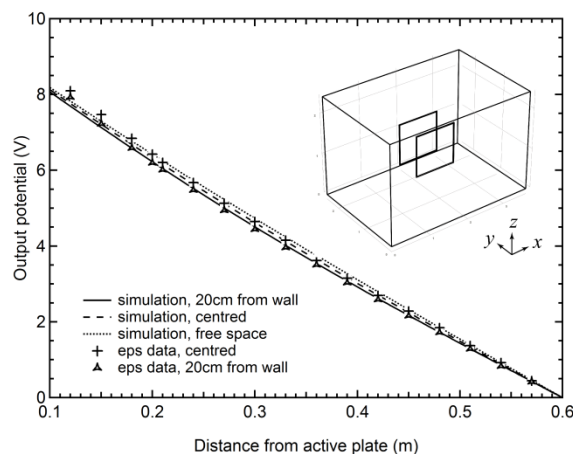
For simulations, we make use of COMSOL Multiphysics to produce an electric field distribution to mirror the excitation and spatial conditions in the experiments. An identical wire-frame model of the enclosure and plates was constructed using relevant electrical parameters for aluminium and air.

Three different configurations have been devised for the electric field setup to demonstrate the effect on the field due to the boundary conditions. The first configuration places the source plate 0.2 m in front of the long wall ( $zx$ -plane) of the enclosure, with the remaining dimensions centralised. The second configuration places the plates precisely central to all axes in the enclosure. For these two positional configurations, a pseudo-colour spatial potential plot in the  $yx$ -plane is extracted from the simulations at the mid height of the plates. The final scenario is only achievable in simulation with the plates in infinite free space, ie, no grounded enclosure.

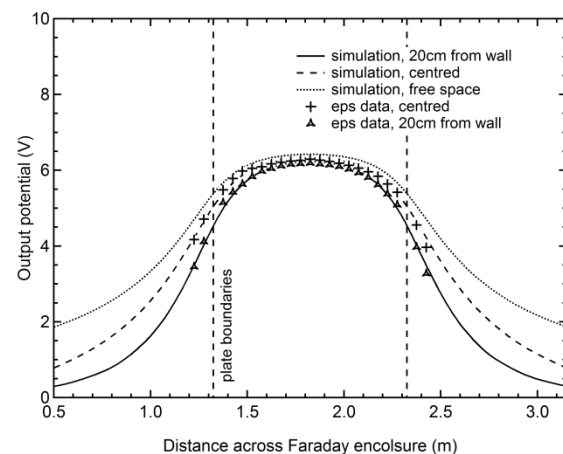
The  $x$ -axis measurements for all of these configurations are made 0.2 m, parallel to and in front of the source plate, i.e. between the plates. The practical measurement procedure was to position the EP sensor electrode, step out of the Faraday enclosure, seal the door, then to average the signal on a digital oscilloscope 64 times. The only active device in the enclosure was the EP sensor and its d.c. battery pack situated behind the grounded plate. The a.c. drive signal and EP sensor signal were carried through interface connectors in the enclosure wall.

### 3. Results

Figure 1 shows the simulated and experimental data for the  $y$ -axis measurements through the centre of the plates for the three configurations. These are a function of the output voltage for a given distance from the source plate. In the case of the EP sensor output, these are the averaged peak-to-peak output voltage measurements after a calibration factor is applied to compensate for the gain of the EP sensor in relation to the ideal results. An average calibration factor, of 0.92, was empirically calculated using a best fit to all the results. The EP sensor data is shown as points in figure 1 and the lines in the same figure are the matching simulation results. It can be seen that after the calibration factor is applied, the experimental results are in excellent agreement with the simulations. Figure 1 only shows results from 0.1 m, to the grounded plate at 0.6 m, due to the non-ideal behaviour of the EP sensor close to the active plate. This is due to direct capacitive coupling between the sensor electrode and the plate as was reported earlier [6]. It should be noted that a significant curvature is seen both in the simulations and the measurements. This result is mainly due to the aspect ratio of the structure. However, the proximity of earthed objects and finite boundary conditions also affects this behaviour as may be seen by comparing the three cases shown in figure 1.



**Figure 1.** Simulation and experiment for  $y$ -axis. Configurations are; source plate 0.2 m from enclosure wall; plates centred; free space. The insert shows a wire frame model with axes.

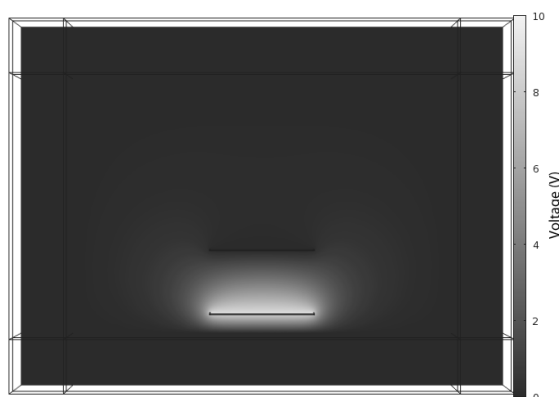


**Figure 2.** Simulation and experiment for  $x$ -axis at mid-height and 0.2 m in front of active plate. Configurations are; source plate 0.2 m from enclosure wall; plates centred; free space.

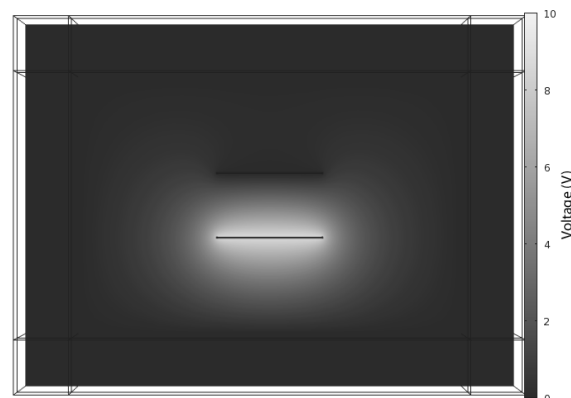
Figure 2 shows the data in the  $x$ -axis along the mid-height of and 0.2 m in front of the source plate. The output is a function of position with reference to the  $yz$ -plane edge wall of the enclosure. The vertical hatched lines in figure 2 show the edges of the plates. The lines represent the simulated data and the points the corresponding measurements. The curvature seen in figure 2 in the  $x$  direction is expected. The curvature persists within the plates due to the fringing created by the low aspect ratio of the parallel plate structure. Both the magnitude and field profile are in good agreement with the simulations.

Figure 3 shows a pseudo-colour plot of the simulation of the spatial potential between the plates, positioned 0.2 m from the long wall of the enclosure. The voltage data is extracted for the section through the mid-height of the plates, showing how the potential falls off to the grounded surroundings. The wire frame drawn depicts the enclosure boundary with a buffer margin outside this, used to simulate ground at infinity in the free space computations. The rate of voltage change over distance due to the nearby grounded wall suggests a confined field near the source plate. Figure 4 on the other hand, with the plates positioned central to all axes, shows a pseudo-colour spatial potential plot in the vicinity of the source plate, showing a less compressed field profile. As may be seen from the data

presented in figures 1 and 2 there is a significant difference between the results for being centred within the enclosure and being in free space.



**Figure 3.** Simulated pseudo-colour voltage  $yx$ -plane plot through the mid-height of plates in unbalanced excitation with active plate 0.2 m from enclosure wall.



**Figure 4.** Simulated pseudo-colour voltage  $yx$ -plane plot through the mid-height of plates in unbalanced excitation.

#### 4. Conclusions

The most interesting conclusion which may be drawn from these results is that the field is modified significantly, by the presence of the grounded enclosure, even when the test structure is carefully centralised on all axes. It is also evident that given a single sensitivity calibration the EP sensor is capable of making measurements both of the magnitude and of the field profile of the spatial potential without significantly perturbing the field. As such, this sensor is suitable for mapping of spatial potential, and hence the resulting electric field, with an ultimate sensitivity which has been demonstrated to be at the micro-Volt per metre level in an earlier publication [6]. Future work will concentrate on producing an open calculable electric field test structure which does not require the presence of a screened enclosure.

#### Acknowledgements

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